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14. THE MESA ACCELEROMETER FOR SPACE APPLICATION

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ABSTRACT

An electrostatically suspended proof mass is used to measure acceleration in the submicro-g range.

Since no fixed mechanical suspension (such as springs or strings) is used, the constrainment scaling can be changed electrically after being placed in orbit.

A single proof mass can sense accelerations in three axes simultaneously.

It can survive high-g pyrotechnic-generated shocks and launch environments while unpowered.

1.0 INTRODUCTION

The word MESA is an acronym for Miniature Electrostatic Accelerometer (Figure 1). This accelerometer is designed specifically for low-g applications. Full scale is typically ±1 milli-g up to ±25 milli-g's. Often two more sensitive ranges are also provided.

What is significantly different about this accelerometer is that it has no mechanical spring. In other accelerometers used for low-g measurements, the mechanical spring is a large contributor to the bias instability and the time-dependent drift and temperature coefficient of the bias. The MESA does not have a mechanical spring; the MESA's proof mass is electrostatically suspended in all three axes. When it is in operation, there is absolutely no physical contact betwen the proof mass and any other part of the accelerometer.

FEATURES:

- ELECTROSTATIC SUSPENSION AND CONSTRAINMENT IN THREE AXES
- DESIGNED SPECIFICALLY FOR VERY LOW-G APPLICATIONS
- AUTOMATIC OR MANUALLY COMMANDED RANGE SWITCHING
- SURVIVE HIGH-G LAUNCH ENVIRONMENT

HISTORY:

- OVER 40 SINGLE-AXIS VERSIONS
- NINE THREE-AXIS VERSIONS
- THREE SINGLE-AXIS UNITS OPERATED FLAWLESSLY FOR FIVE YEARS IN SPACE

FIGURE 1. MINIATURE ELECTROSTATIC ACCELEROMETER (MESA)

Even though it is intended to measure very low g's, it is capable of surviving extreme launch environments. The MESA is unpowered during launch. In this nonoperating mode, it has been qualified to 15 g's linear acceleration, 20 g's rms random vibration, and 6000 g's pyro shock. After the high g's associated with launch have passed, the MESA can be powered up, and will be outputting valid low-g data within one minute.

Our first MESA accelerometers were single-axis instruments; although the proof mass is always electrostatically suspended in all three axes, we only instrumented one of the axes. Approximately 40 of these single-axis MESAs were built and flown. We were later asked if we perhaps could change the MESA to a three-axis version using a single-proof mass. We successfully instrumented the other two axes, yielding a three-axes MESA. Nine of these instruments have been built and flown.

2.0 HARDWARE

The MESA hardware is shown in Figure 2. The proof mass is a thin-walled, flanged cylinder. The inside diameter is approximately a half-inch and the length about one inch; the flange in the middle is about 1½ inches in diameter. The proof mass fits over the carrier, which is a ceramic rod with eight electrodes plated onto it. The outside diameter of the carrier is slightly smaller than the inside diameter of the proof mass, resulting in a very small radial gap between them when the proof mass is "suspended". The eight electrodes on the carrier are used in four constrainment loops to provide constrainment against linear and angular acceleration in two orthogonal axes.

On either side of the proof mass flange there are forcer assemblies. On each forcer there are three annular rings facing the proof mass flange. The middle ring on each forcer is used in a differential capacitive bridge for proof mass position sensing. The inner and outer rings on each forcer are used to generate the electrostatic rebalance forces required for constrainment. Between the forcers there is a

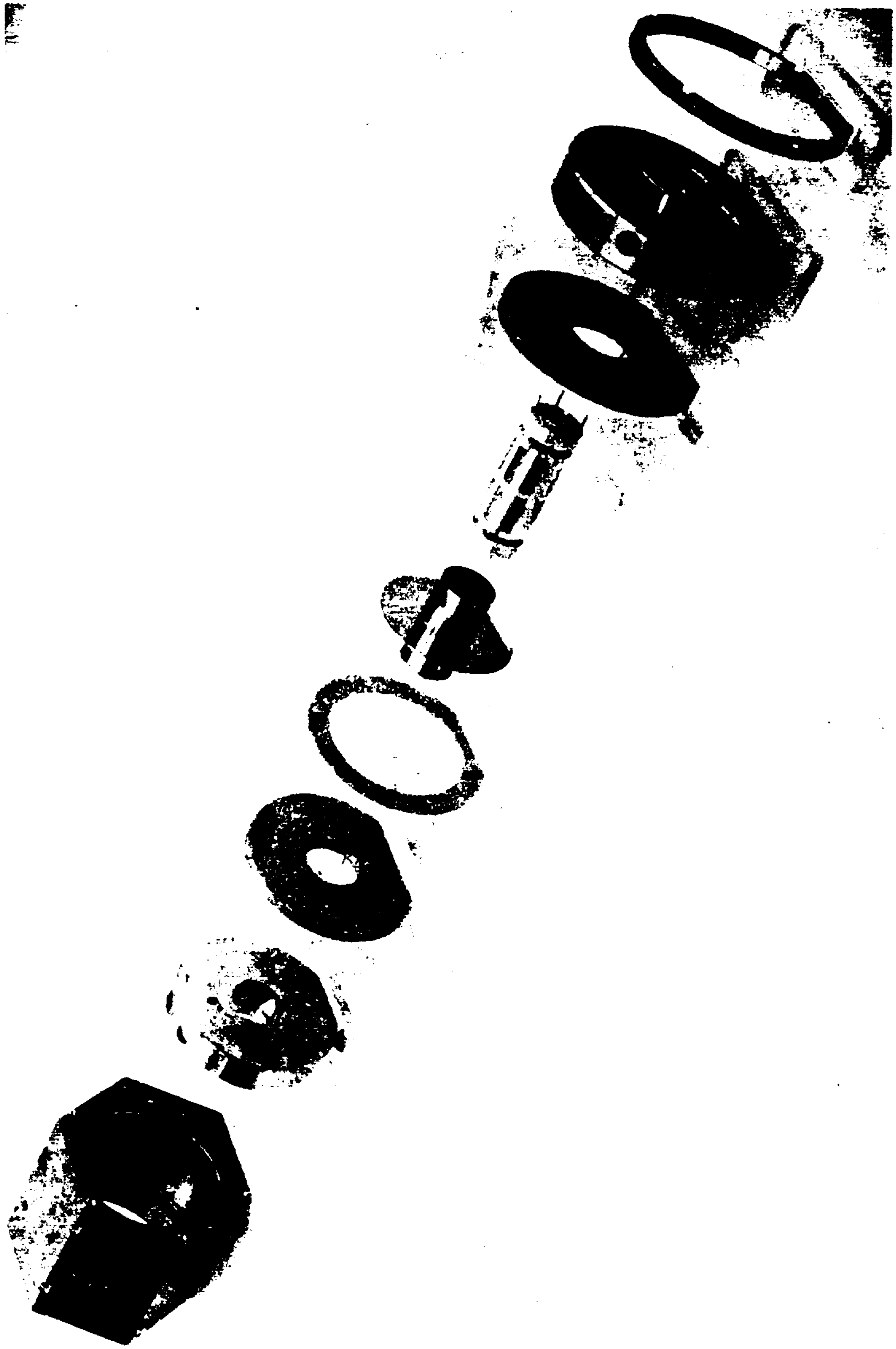


FIGURE 2. MECHANICAL ASSEMBLY

ceramic annular ring spacer which is slightly thicker than the proof mass flange; this difference establishes the pickoff and forcing gap. On the back side of each forcer there is a metallic retainer that supports an end of the carrier.

All the previously mentioned items are positioned in the housing and are held against a ledge in the hexagonal housing by a ring nut. The hermetically sealed housing is filled with a mixture of 90% dry nitrogen and 10% helium to provide gas damping of the proof mass for stable constrainment loop operation, and to protect the proof mass during the unpowered high-g launch environment.

Hermetically sealed terminals in the housing flats are used to connect the carrier and forcer electrodes to pickoff preamplifiers and forcer networks on p-c boards attached to the six housing flats.

The accelerometer has three mounting pads which are used to attach it to the vehicle structure at which the input acceleration is to be measured.

3.0 CONSTRAINMENT LOOPS

Figures 3 and 4 show the force rebalance loops in the Z axis and in the cross axes (X and Y), respectively.

A typical constrainment loop is shown in more detail in Figure 5. A cube-shaped proof mass is shown here (more will be mentioned about that later), but the principle of operation is independent of the proof mass shape.

The pickoff excitation generator provides push-pull sine wave excitation to a capacitive differential pickoff bridge consisting of two equal fixed capacitors, C_1 and C_2, and the capacitances between the two electrodes and the proof mass. The output of the bridge is summed by equal fixed capacitors C_3 and C_4, and is applied to the preamplifier.

If there is no input acceleration, the proof mass is centered between the two electrodes, causing the bridge to be balanced. The preamplifier input is thus zero, and no constrainment force is developed.

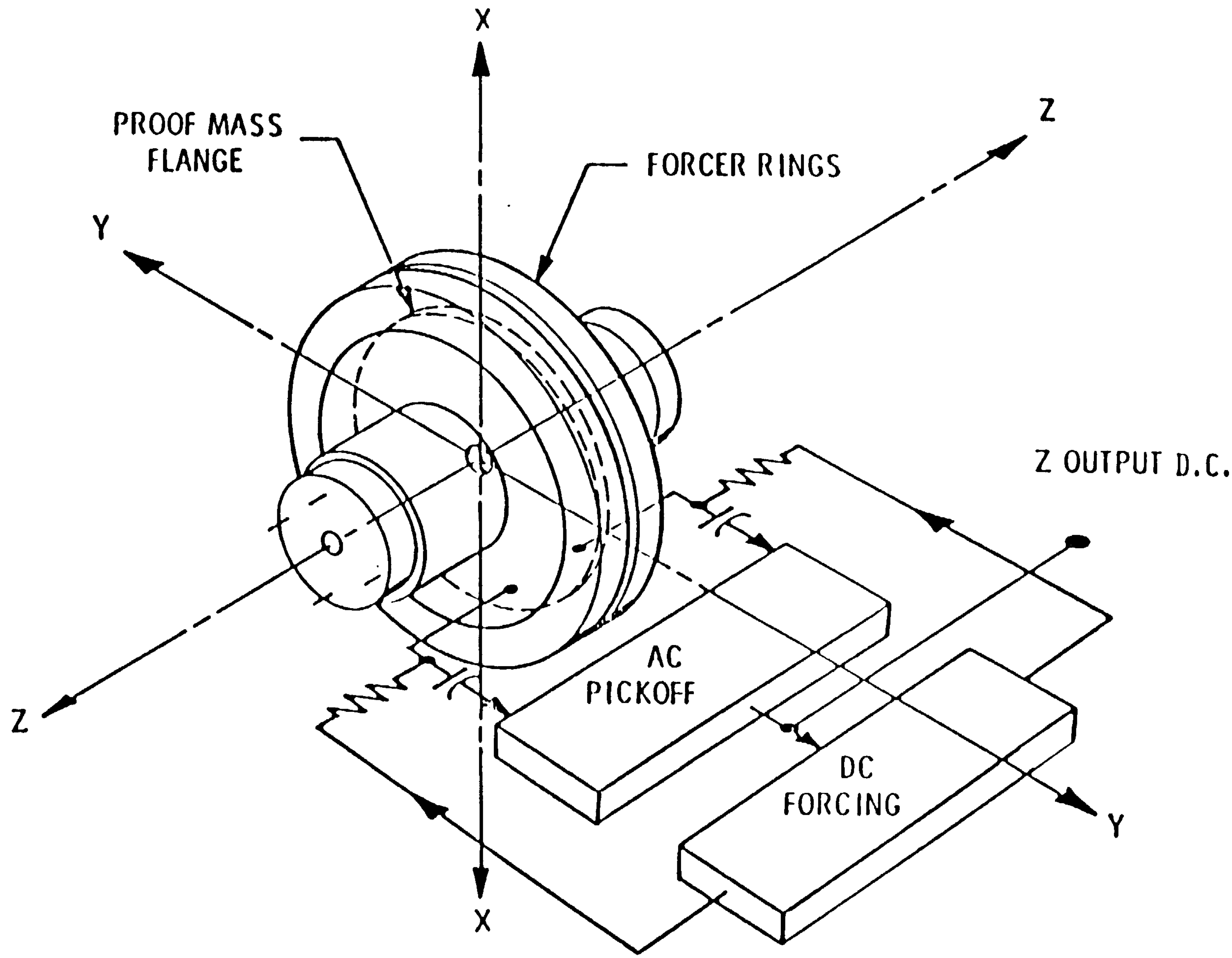


FIGURE 3. FORCE REBALANCE LOOP, Z AXIS

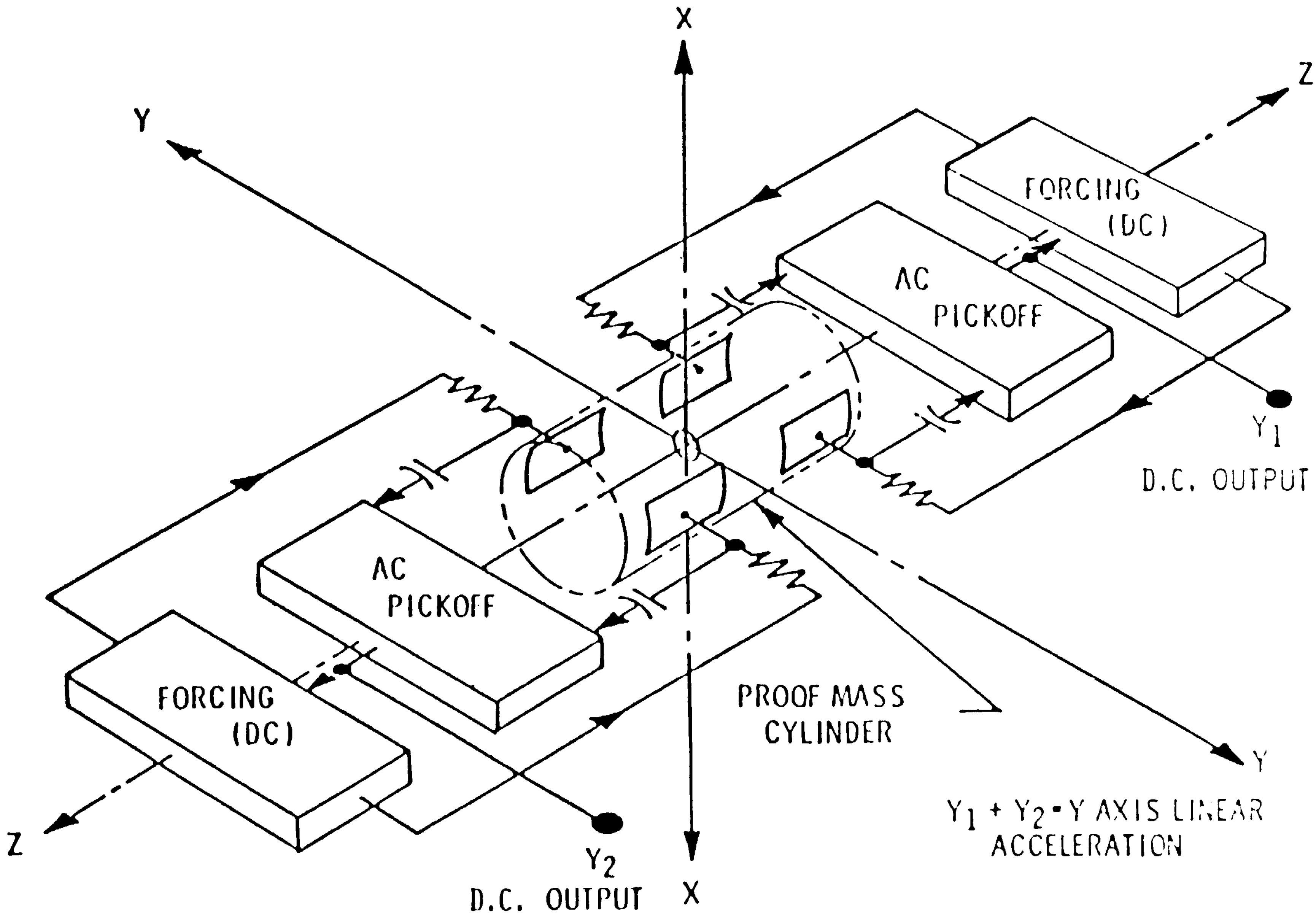
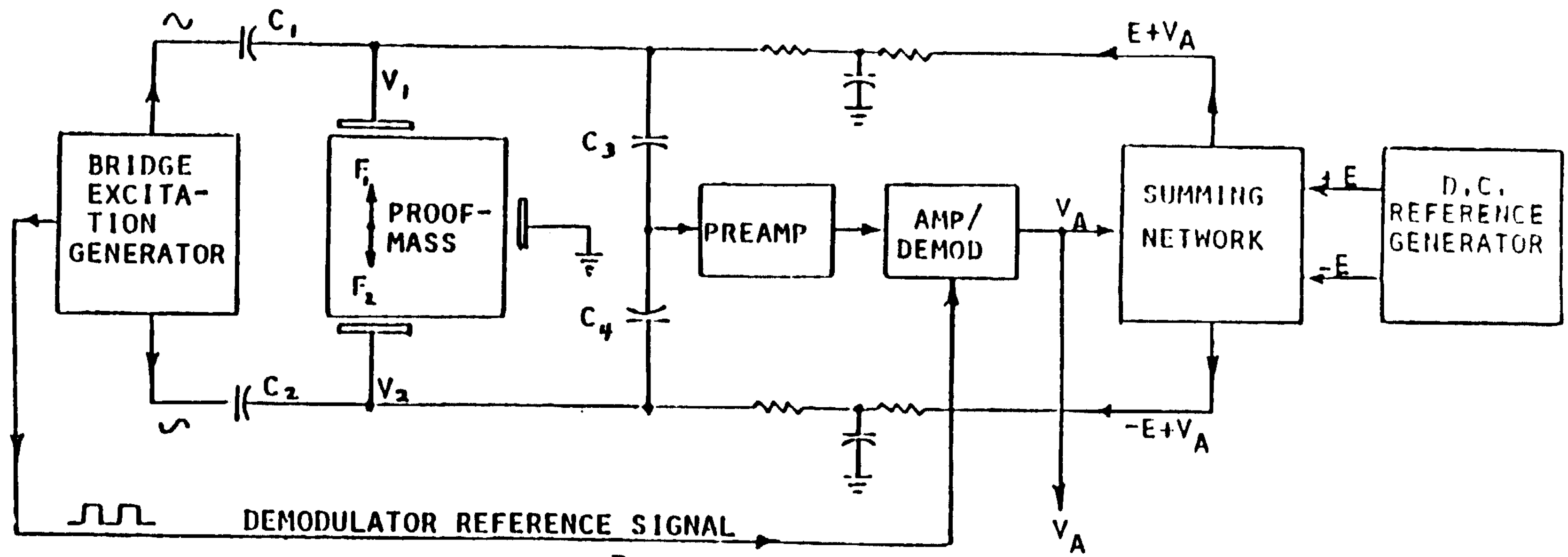


FIGURE 4. FORCE REBALANCE LOOP, X AND Y AXES (Y ONLY SHOWN)



GENERAL EQUATION: $F = \frac{4.4 \times 10^{-7} K_A V^2}{\delta^2} = KV^2$

DEFINE $V_1 \equiv (E + V_A)$ AND $V_2 \equiv (-E + V_A)$

THEN $F_1 = KV_1^2 = K(E + V_A)^2$

AND $F_2 = KV_2^2 = K(-E + V_A)^2$

$(F_1 - F_2) = K(E + V_A)^2 - K(-E + V_A)^2 = 4KEV_A$

FIGURE 5. TYPICAL CONSTRAINMENT LOOP

If there is an input acceleration, the proof mass moves very slightly from its centered position. This causes the bridge to become unbalanced. The resultant bridge unbalance voltage is amplified by the preamplifier and amplifier, and then is phase-sensitive demodulated to provide d-c voltage, V_a.

The summing network combines error signal V_a with d-c reference voltages +E and -E to generate the two required d-c constrainment voltages, V_1 and V_2.

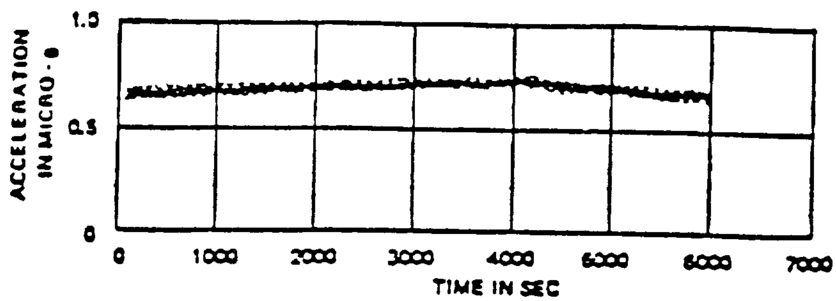
As shown in Figure 5, V_1 and V_2 cause forces F_1 and F_2, each one attracting the proof mass toward its forcer. The differential force ($F_1 - F_2$) is equal to $4KEV_a$; this constrainment force acts as a positive electrical spring to constrain the proof mass. Since the constrainment loop output voltage V_a is directly proportional to the constrainment force ($F_1 - F_2$), V_a is directly proportional to input acceleration.

4.0 FLIGHT DATA

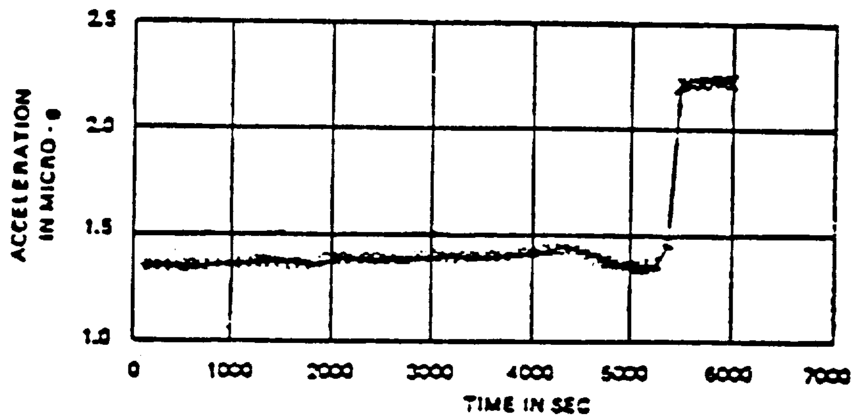
Figure 6 shows some data taken in 1968 from a signle axis MESA used on the SERT II (Space Electric Rocket Test) vehicle in earth orbit. The MESA was used to measure acceleration due to thrust from an ion engine. The upper plot shows the expected 0.7 micro-g acceleration due to the gravity gradient; the ion engine was not thrusting at this time. The middle plot shows the acceleration with 30% and 80% engine thrust. The lower plot shows the acceleration with 100% engine thrust. There is an interesting phenomenom shown in this last plot; as far as we can determine, the perturbation in the acceleration was caused by the South Atlantic magnetic anomaly.

Figures 7 through 12 show some flight data from the 3-axes MESA used on spacecraft in an elliptical earth orbit.

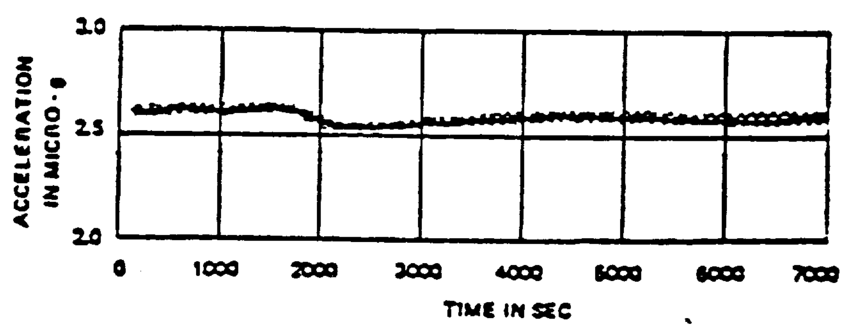
Figures 7 through 9 are for normal flight operation. The MESA Z axis measured the along-track component of the vehicle acceleration. The MESA Z axis bias was approximately +3 micro-g's (the indicated



MESA Output for Gravity Gradient Input



MESA output with 30% and 80% Engine Thrust



MESA output with 100% Engine Thrust

FIGURE 6. SERT II FLIGHT DATA

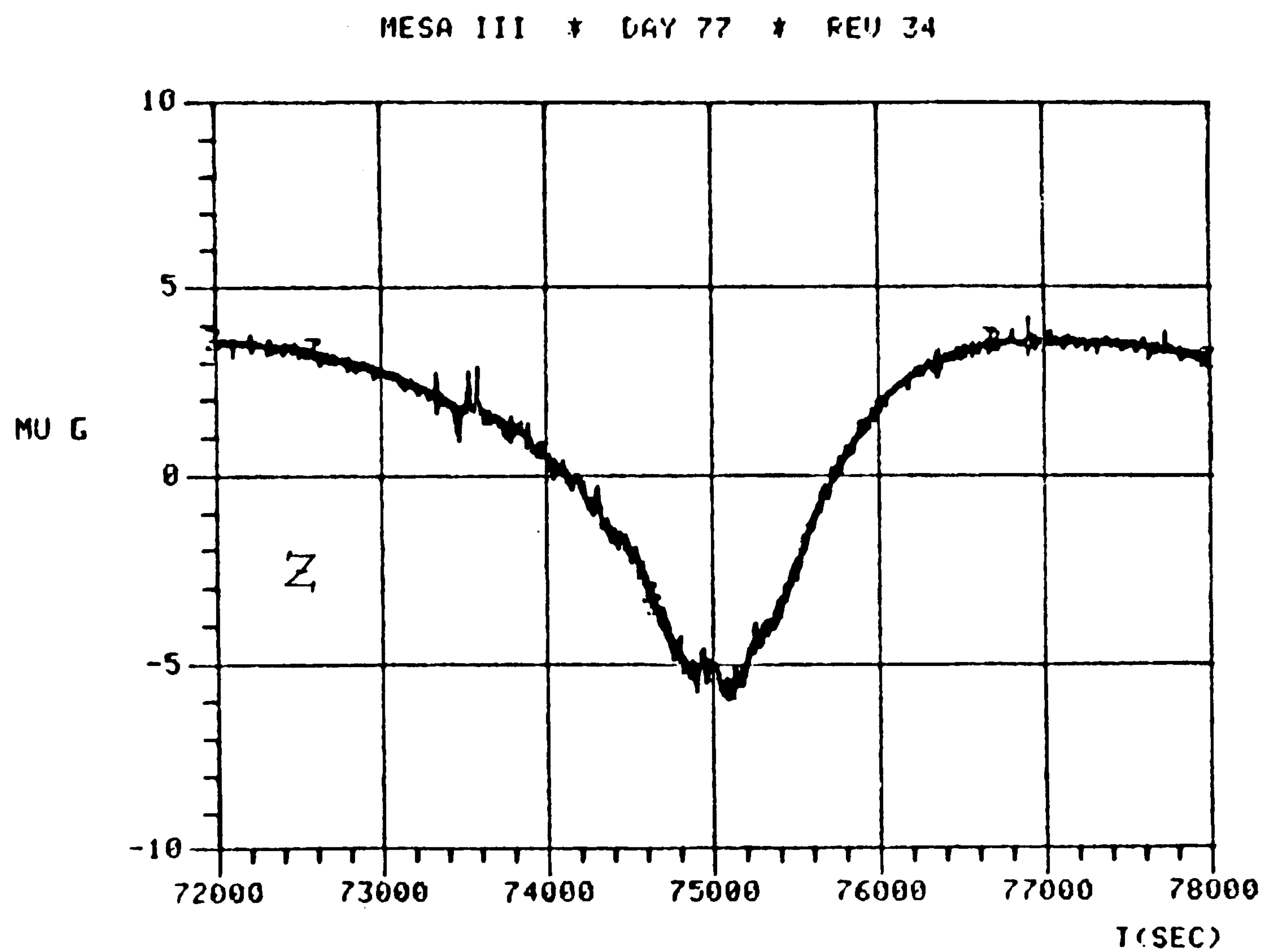


FIGURE 7. ALONG-TRACK COMPONENT

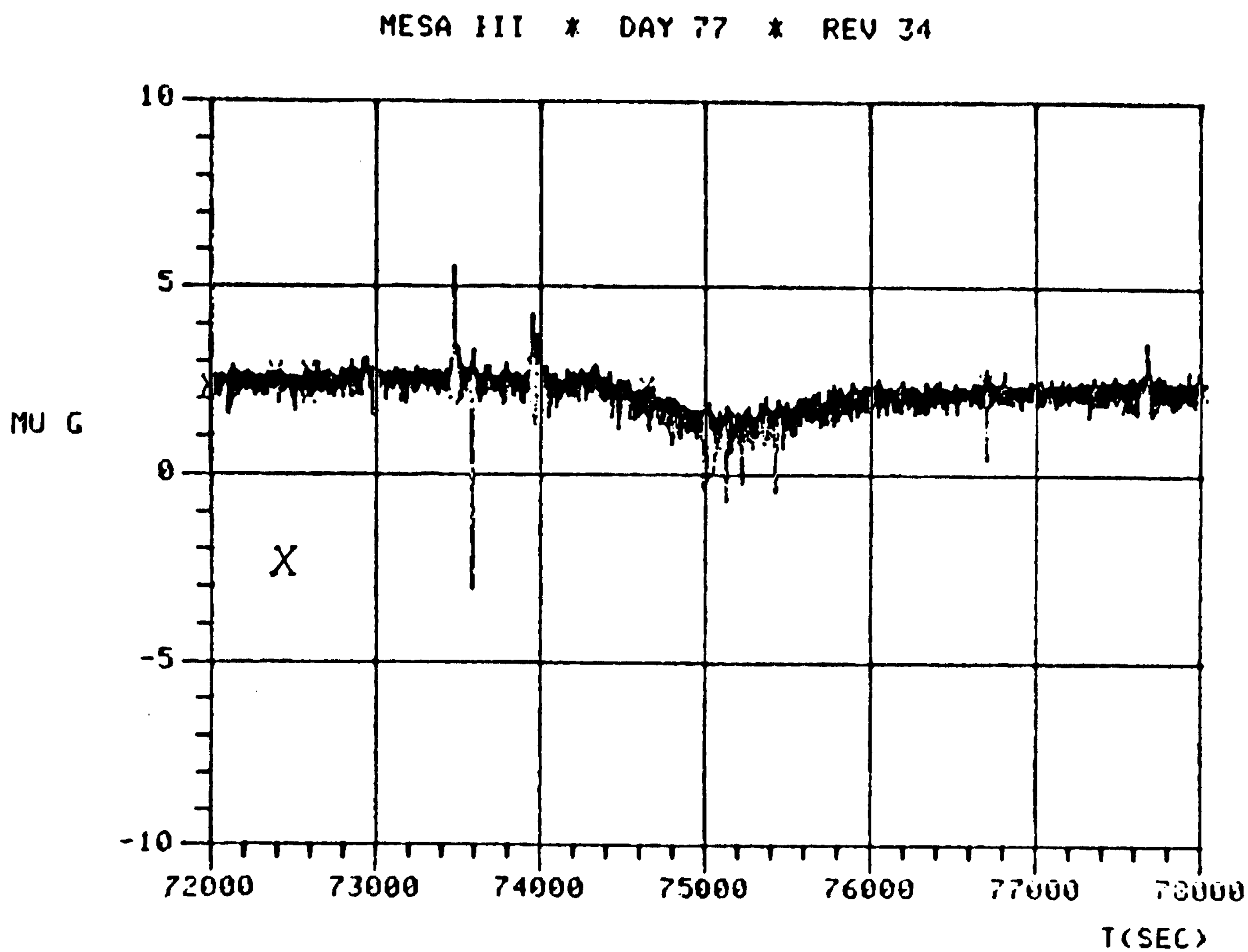


FIGURE 8. CROSS-TRACK COMPONENT

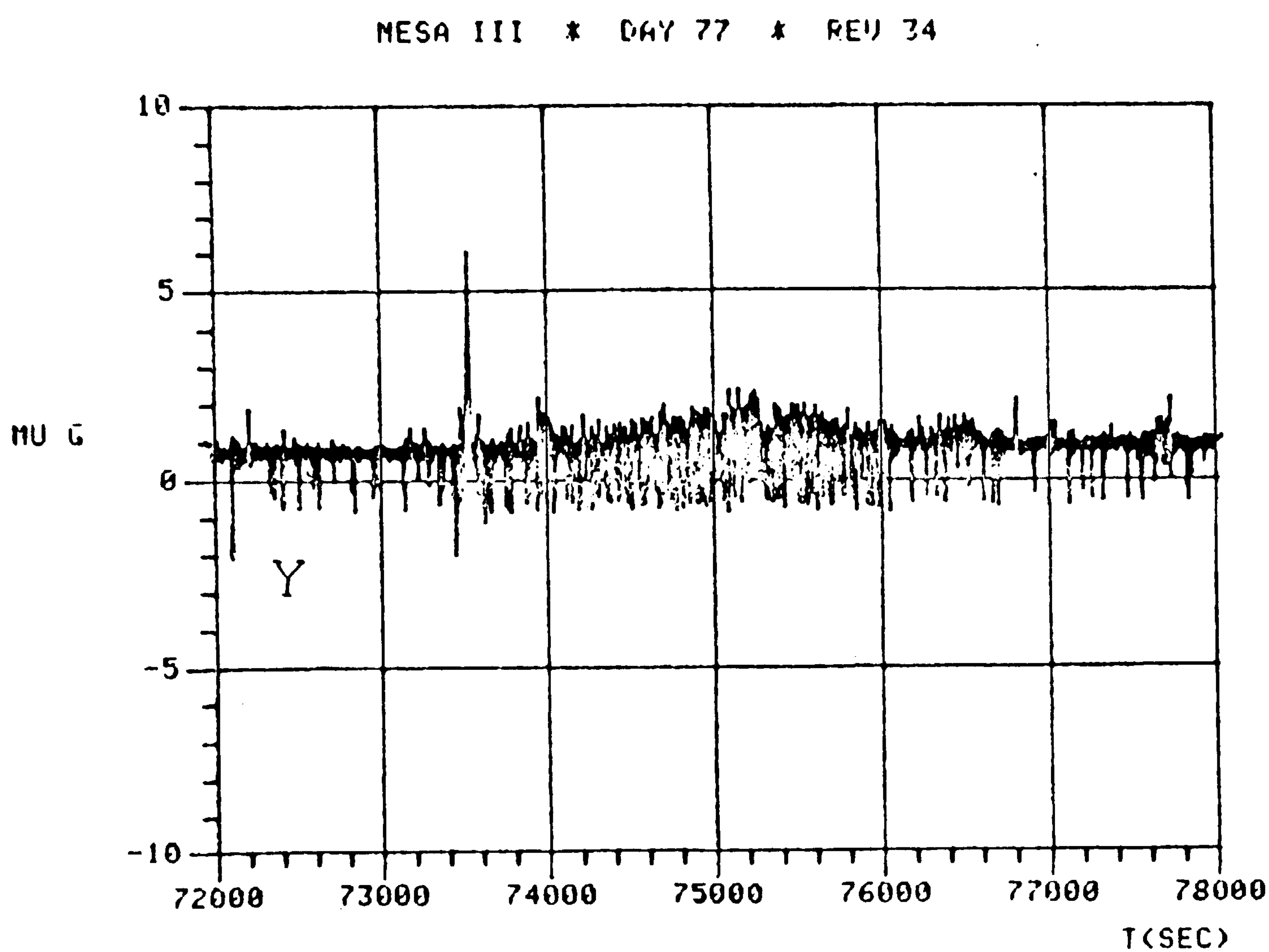


FIGURE 9. RADIAL

acceleration at apogee). As the vehicle approached perigee, the drag acceleration increased by approximately 9 micro-g's, resulting in an indicated acceleration of -6 micro-g's.

Figures 8 and 9 show MESA flight data in the X (cross-track component) and Y (radial component) axes. The spikes in the data are primarily from accelerations due to firing of the vehicle's attitude thrusters. Readily evident is the increased frequency of attitude thruster firings near perigee.

Figures 10 through 12 show data during an orbit-adjust thruster firing. The along-track component acceleration is approximately 10,000 micro-g's. The plots of the cross-track and radial components show some vehicle oscillations during the orbit-adjust thruster firing.

The MESA for which flight data are shown in Figures 7 through 12 is an autoranging instrument. Each axis has three ranges. During normal flight operation (Figures 7 through 9), all three axes were in their most sensitive ranges. When the acceleration suddenly increased due to firing of the orbit-adjust thrusters, the autorange circuitry caused upranging of the ranges as required to provide valid data. After the orbit-adjust thruster firing was completed, the autoranging circuitry caused downranging to the most sensitive ranges.

5.0 DEVELOPMENT AND FLIGHT HISTORY

As shown in Figure 13, development of the Bell electrostatic accelerometer started in 1958 with the ESA (Electrostatic Accelerometer); this was a larger version of the present MESA. Single-axis MESA's were flown on spacecraft, starting approximately 1963. Of particular interest is the MESA used on the Atmosphere Explorer Satellite AE-C. On this spacecraft there were three single-axis MESA's in a triad. This unit operated for five years in orbit until the satellite itself fell out of orbit and burned up.

In 1978, deliveries and flights of the three-axis version of the MESA began. Most have been used for navigation and for air density measurements. An exception is the MESA supplied for the Spacelab 3

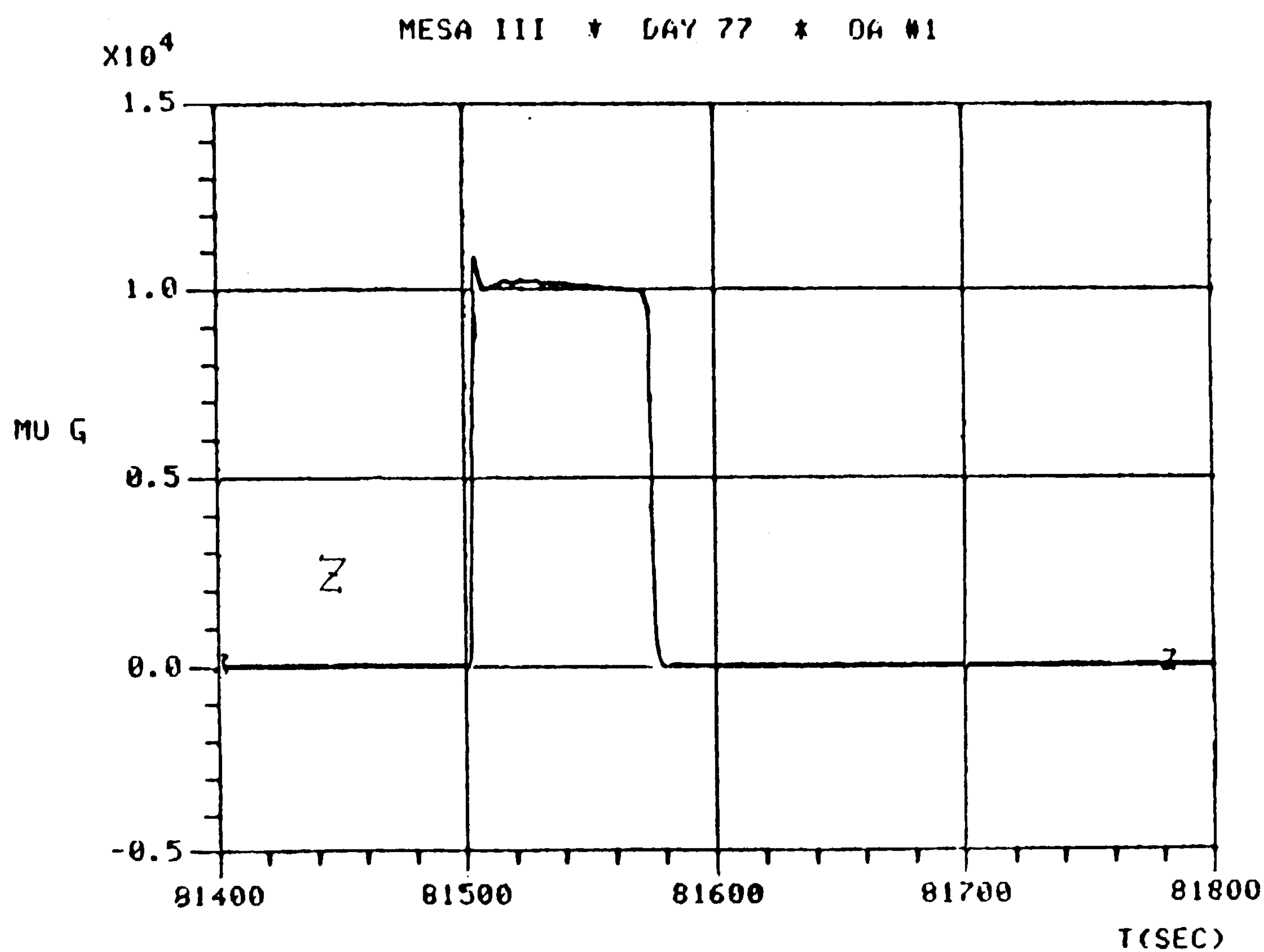


FIGURE 10. ALONG-TRACK COMPONENT

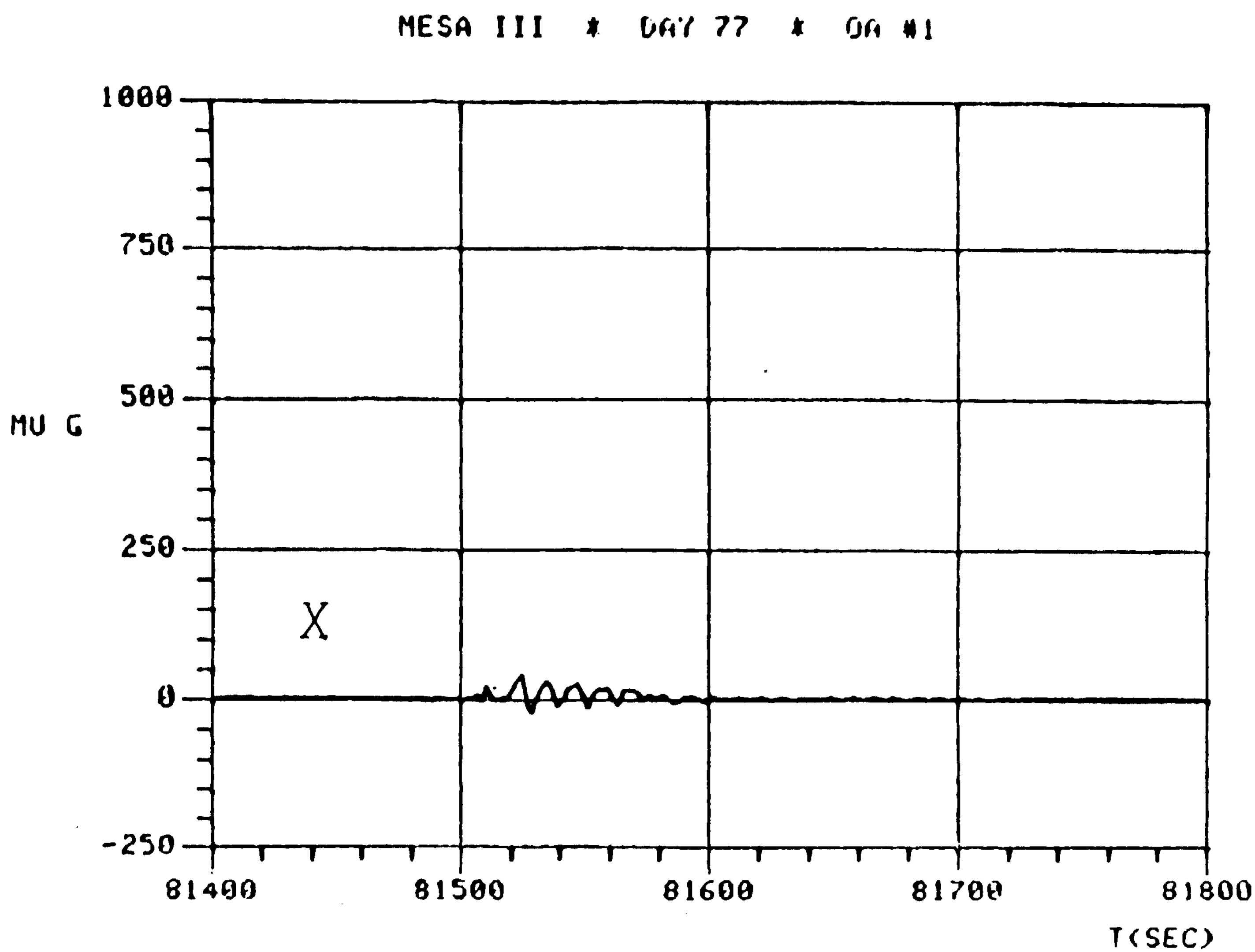


FIGURE 11. CROSS-TRACK COMPONENT

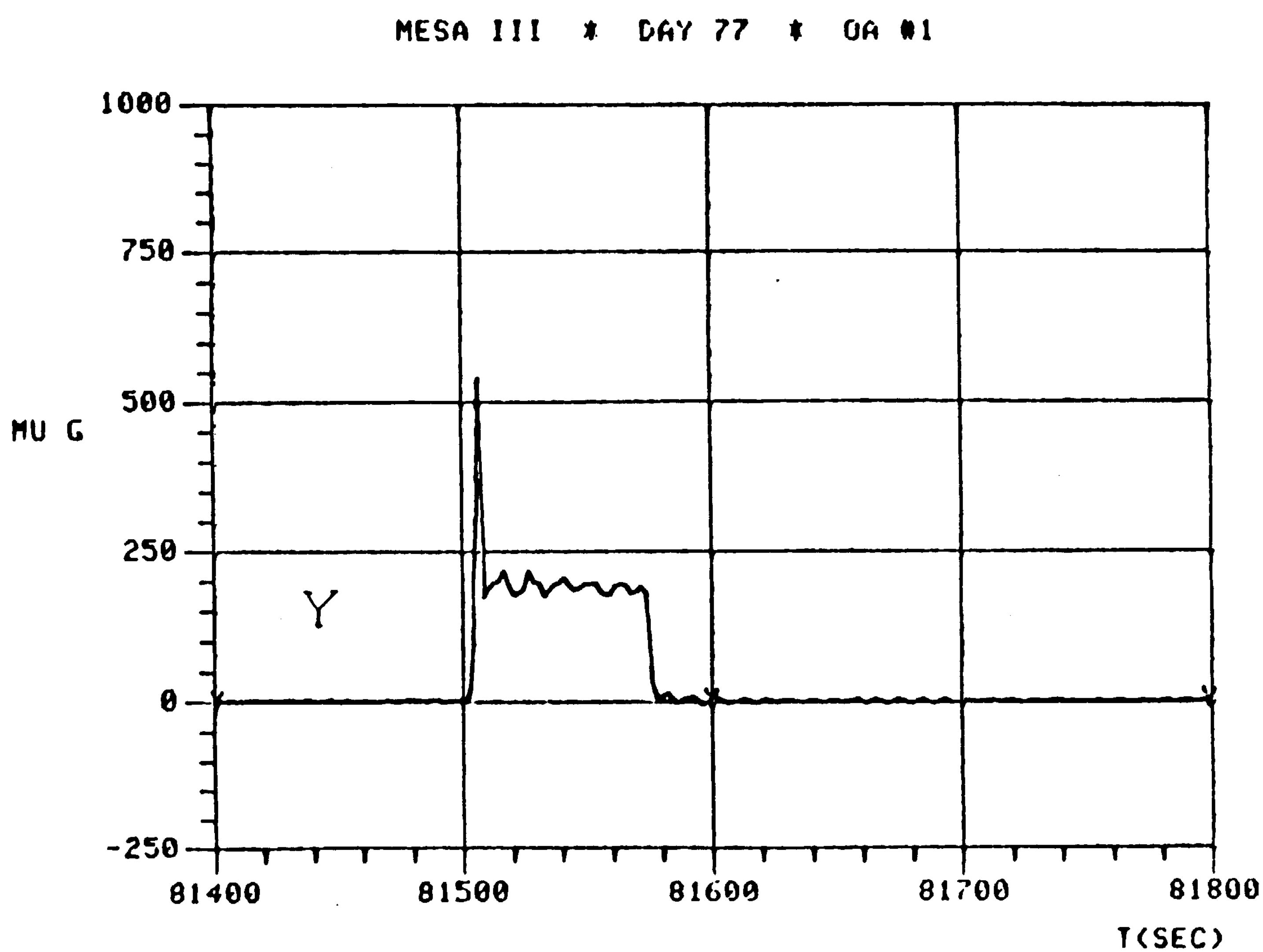


FIGURE 12. RADIAL

[SINGLE AXIS]	1958 - 1963	ESA, BASIC DEVELOPMENT (5)
	1963 - 1965	NASA LEWIS, FIRST FLIGHT SATURN 1B, JUNE 1966 (2)
	1964 - 1966	AIR FORCE, GENERAL DYNAMICS, CLASSIFIED (3)
	1966 - 1967	LOGACS (LMSC), FLOWN ON AGENA, APRIL 1967 (3)
	1966 - 1970	CANNONBALL/SPADES AFGL (12)
	1969 - 1970	MSFC, MASS ATTRACTION (1)
	1967 - 1968	SERT II, NASA LEWIS (2), ION ENGINE THRUST
	1968 - 1969	AF, MOL, GE, (9)
	1968 - 1969	PROJECT 110, LMSC, (7), ORBITAL DRAG MEASUREMENT.
	1970 - 1974	ATMOSPHERE EXPLORER SATELLITE AFGL/NASA, (9), AE-C 5 YEARS IN ORBIT.
	1975 - 1976	S73-5 AIR FORCE/BOEING SATELLITE, AFGL, AIR DENSITY (1).
	1978	ROCA, AFGL, (1), 90° ROTATING TABLE - SINGLE AXIS.
[THREE AXIS]	1978 - 1981	NAVPAC DMA/AFGL NAVIGATION AND AIR DENSITY (6)
	1979 - 1981	SL-3 MATERIAL PROCESSING (2) - FIRST SHUTTLE FLIGHT (2).
	1982 - 1984	S85-1 AIR FORCE - AIR DENSITY (1).
	1984 - 1986	OARE - NASA LANGLEY (1) WITH IN-ORBIT CALIBRATOR.
	1985 - 1986	CUBE - DEVELOPMENT - COMPANY SPONSORED.

FIGURE 13. ELECTROSTATIC ACCELEROMETER HISTORY

Material Processing in Space experiment; a wideband (50 hertz) instrument with an autoranging sampled data system was specified for this application. We are now working on a three-axis MESA for the OARE (Orbital Acceleration Research Experiment) for NASA/Langley; this MESA will be mounted in a centrifuge for veification of the calibration in orbit. As will be discussed in the next section, we are also developing a three-axes MESA with a cube proof mass.

6.0 NEW DEVELOPMENTS

An improved version of the MESA is now under development (see Figure 14). This new instrument uses a cube proof mass in place of the flanged cylinder, thus providing constrainment against six degrees of freedom instead of five. Elimination of the curved electrode and proof mass surfaces also results in equal performance in all three axes. A development model has been fabricated and testing will start in the near future.

The proof mass and electrode configuration is shown in Figure 15. The proof mass is a cube made of beryllium. Its outside dimensions are a nominal 0.5 inch, and the mass is one gram. Facing each of the six cube faces is a pair of electrodes. An electrode together with the corresponding electrode on the opposite face are used for the pickoff position and forcing functions in one of the six constrainment loops. Use of six pairs of electrodes in six constrainment loops provides constrainment against linear acceleration in three axes and against angular acceleration around three axes.

Figure 16 shows the force rebalance loop for the Y axis. The loops for the X and Z axes are identical. The Y output shown is the sum of the signals from the two constrainment loops; this output is proportional to Y axis linear acceleration. If the two constrainment loop outputs are differenced instead of summed, the resulting output will be proportional to the angular acceleration around the Z axis.

FEATURES:

- ELECTROSTATIC SUSPENSION IN 3 AXES
- PROOF MASS SYMMETRICAL IN ALL THREE AXES
- CONSTRAINED AGAINST 6 DEGREES OF FREEDOM
  (3 TRANSLATION, 3 ROTATION)
- MAY BE CALIBRATED IN 1G GROUND ENVIRONMENT
- SENSITIVITY GOAL IS 10^{-11}G
- PROOF MASS EXTREMELY RUGGED
- ORTHOGONAL ELECTRODES FOR MINIMUM CROSS COUPLING

FIGURE 14. 3 AXES CUBE PROOF MASS DEVELOPMENT

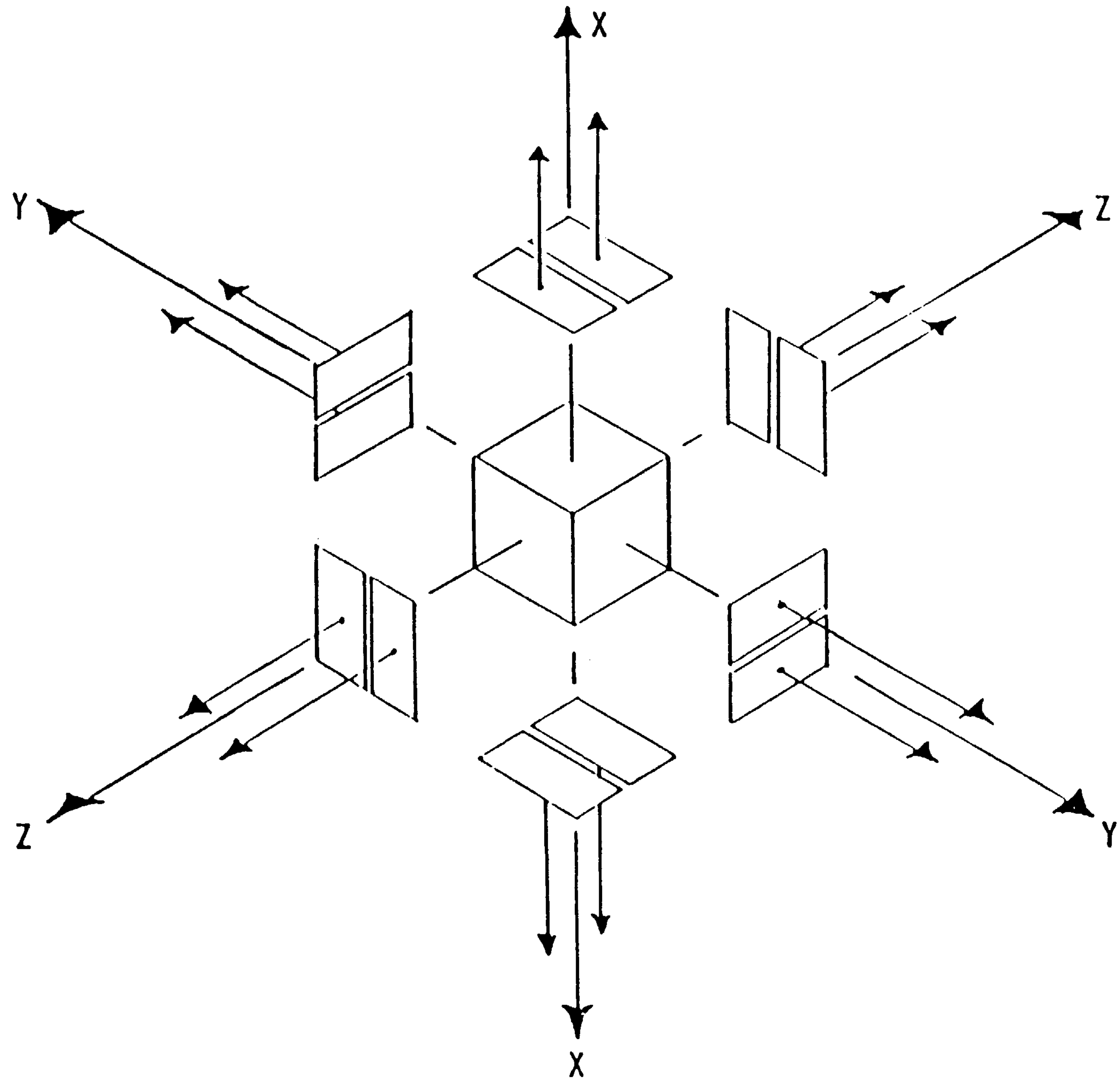


FIGURE 15. PROOF MASS AND ELECTRODE CONFIGURATION

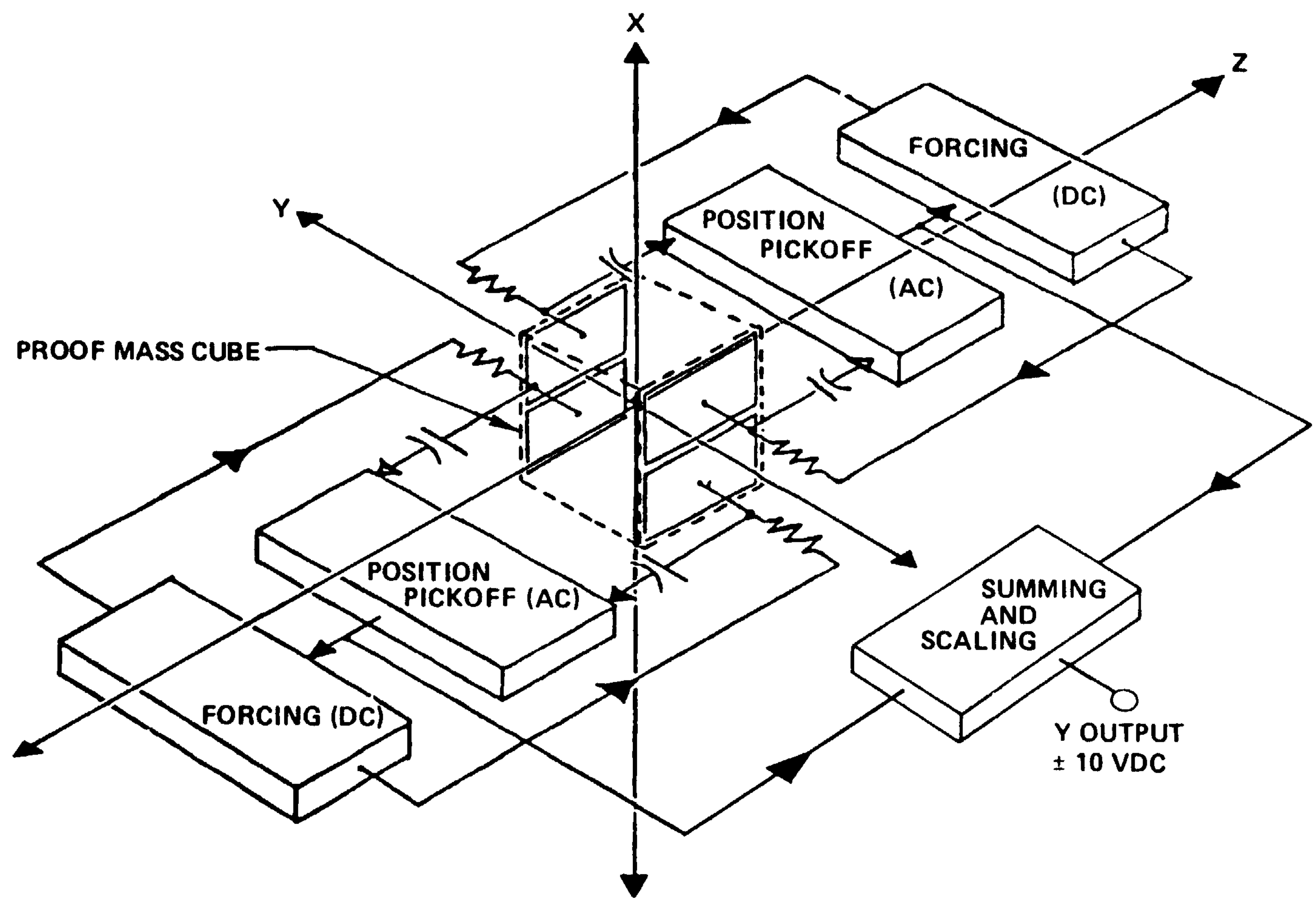


FIGURE 16. FORCE REBALANCE LOOPS (Y ONLY SHOWN)

The MESA cube proof mass mechanical assembly is shown in Figure 17. Each of the six identical electrode assemblies contains two electrodes which are insulated from each other and from the metal base by a ceramic insulator.

The gap between the electrodes and the proof mass is a nominal 0.002 inch and is maintained by the cylindrical-shaped cage into which all six electrode assemblies and the proof mass are assembled. The cage assembly fits inside the hermetically sealed hexagon-shaped housing, with the 12 electrode terminals exiting radially at both ends.

The six constrainment loop preamplifiers on individual p-c boards are attached to the external housing flats to provide short direct connections to the internal electrodes. The output of each preamplifier is at a low impedance and high signal level for connection to the rest of the constrainment loop electronics.

The instrument case has three mounting pads that are used to attach it to the vehicle structure at which the input acceleration is to be measured.

The case is hermetically sealed and filled with a mixture of 90% dry nitrogen and 10% helium to provide gas damping of the proof mass for stable constrainment loop operation, and to protect the proof mass during the unpowered high-g launch environment. The gas pressure is a nominal 1 atmosphere (15 psia).

Preliminary specifications for the Cube Proof mass MESA are given below.

Preliminary MESA - Cube Specifications

Type	Three Axis - Cube Proof Mass
Size	3.5 in. x 5 in. x 9 in.
Weight	5 lb
Power	9 Watts

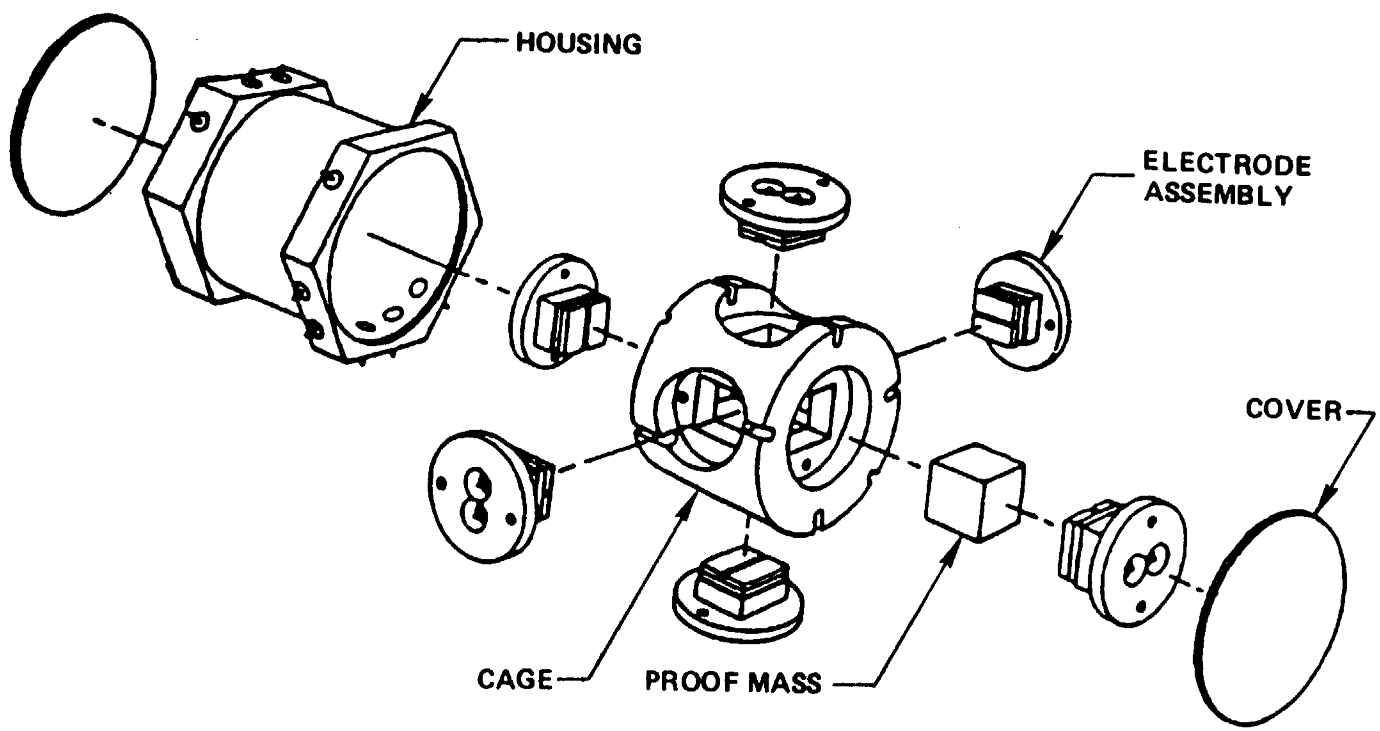


FIGURE 17. MESA CUBE PROOF MASS MECHANICAL ASSEMBLY

Sensitivity	10^{-9} g
± Full Scale (Lowest Range)	10^{-5} g
± Full Scale (Highest Range)	10^{-2} g
Scale Factor Accuracy	
Gnd Test Cal.	0.5%
On Orbit Cal.	0.05%
Output	±10 Vdc = ± Full Scale, all ranges
Ranges Available	3 from 10^{-2} to 10^{-5}
Environment:	
(Nonoperating)	
Temperature:	-25°F to +185°F
Shock:	50g, 8 msec, 3 axes
Vibration:	Sine: 20 to 2000 Hz 10 g's Random: 20 to 2000 Hz 20 g's rms Pyro: 6000 g's
Acceleration:	15g, 3 axes
Altitude:	Space
(Operating)	
Temperature:	-10°F to +160°F
Altitude:	Space

7.0 APPLICATION ENGINEERING

Potential users of low-g accelerometers always face the obvious problem of matching requirements against available instruments. This task is usually complicated by two factors:

1. Lack of precise knowledge of all the environmental and acceleration inputs which the instrument is expected to experience throughout its life, and

2. Lack of precise definition by the accelerometer manufacturer of all its characteristics and performance in terms that match each user requirement.

The questions that the user should ask himself in attempting to select an accelerometer generally fall into the following categories:

1. Maximum available power, weight, and size?
2. Single-axis or 3-axis sensing?
3. Range of input acceleration expected?
4. Maximum frequency of input acceleration to be measured?
5. Accuracy required?
6. Command and data interface requirements?
7. Environmental conditions such as temperature range, launch acceleration, pyro shock, electromagnetic interference levels, etc.
8. Delivery schedule and rate?
9. Dollar budget?

The accelerometer manufacturer, on the other hand, must characterize the instrument in these terms plus present possible options to each requirement that may be considered to accomplish the measurement in the most efficient manner.

Some available options are described in general terms. Precise electrical interface circuits involving data rates, voltage levels, impedances, etc. must be customized for each application.

Typical applications in which these instruments have been used or could be used are:

- Ion engine thrust measurement
- Air Density
- Solar Pressure
- Navigation and Guidance
- Fuel Venting Accelerations
- Mass Attraction
- Gravity Gradient
- Attitude Control
- Vehicle Acceleration Monitoring
- Vehicle Angular Acceleration.

A single package containing the mechanical instrument assembly and its associated electrostatic force rebalance constrainment loops represents the minimum hardware that can be purchased.

Various accessories are available which may be added to this basic hardware to perform a variety of functions. These generally fall into the six major categories listed below.

1. Power input conditioning
2. Signal output conditioning
3. Multiple ranges
4. Temperature control
5. In-flight calibration
6. Special packaging.

Power Input Conditioning

This converts any available input voltage to the voltages required to operate the constrainment loops. Total conditioning would normally include an EMI filter on the input line, a regulator, and a transformer coupled dc to dc converter followed by the normal power supply filter for each of the five dc voltages required.

Signal Output Conditioning

This converts the normal ± 10 Vdc voltages which represent $\pm$ full scale to the desired output voltage and impedance level. It can also convert the dc output to a serial digital data stream and filter and average the output either in analog or digital form.

Multiple Ranges

The constrainment loops may be switched to set full scale input limits at three different levels or ranges. Range selection may be by external command or by an internal autorange circuit. The latter will automatically adjust each axis to the appropriate scale required to accommodate the input acceleration level experienced at that particular time.

Temperature Control

This maintains the accelerometer case within $\pm 1^{\circ}F$ of a pre-set temperature. It is normally used if the environmental temperature range is large and scale factor temperature coefficients established during calibration cannot be used to correct the output data.

In-Orbit Calibration

This should be considered where the full scales selected may be lower than permitted by ground calibration. An alternative is to use higher scales to permit ground calibration and utilize a longer averaging time per data point to obtain the required resolution and sensitivity.

Special Packaging

The accelerometer may be packaged in various form factors. The instrument and its attached preamplifiers, if packaged separately, would occupy a box-shaped volume with dimensions of 3.5 in. x 4 in. x 4 in.

The instrument loop electronics, if packaged separately, is 3.5 in. x 5 in. x 6 in.

If combined in a single package, the total volume is slightly less, as shown on the specification sheets.

If packaged separately, the constrainment loop electronics should not be more than 10 inches from the instrument package. The accessory circuits described in the above six paragraphs may be located up to 48 inches from the constrainment loop electronics.

A single package configuration is always the most efficient from the standpoint of cost, volume, and performance.